AI Motorvators
Technical paper

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1. System Description
   A. Mobility.

We are planning on entering a 4-wheel purpose built vehicle for the competition. Ground contact will be achieved using off-road tires. The wheel will be arranged in a standard automotive layout with 2 wheels in front providing steering control. All 4 wheels will provide braking capabilities. Motive power will be supplied by the rear wheels (2WD).

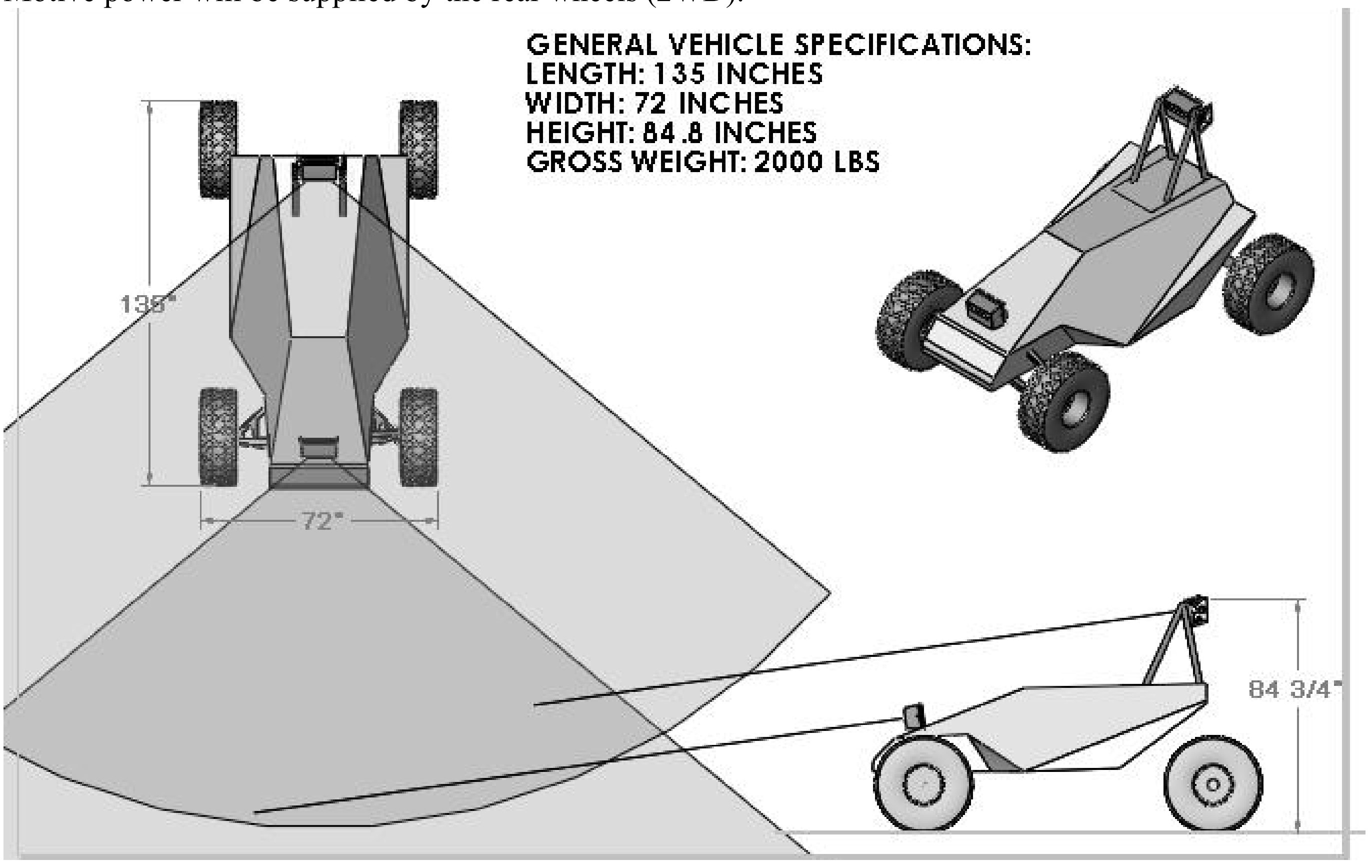

Figure 1- General Dimensions

Steering will be effected by use of a servomotor to turn a standard automotive steering box. The servomotor will be controlled using Pulse Width Modulation and set point via a commercial 24 volt DC motor controller. An automatic transmission will handle gearshifts operated by a servo shift mechanism. Throttle will be applied via closed loop servomotor and a mechanical linkage. Braking will be accomplished using standard automotive 4 wheel hydraulic brakes actuated by a double redundant pneumatic system.

The primary source of pneumatic pressure will be two 12 volt air compressors each supplying 2.6 CFM to a 5 gallon tank. The tank will be pressurized to 60-PSI system pressure. In addition a separate 2.5 gallon tank will be held in reserve to provide emergency pneumatic pressure in the event of system pressure loss. The emergency tank will be filled by normal compressor operation, but isolated by a check valve to maintain it's pressure independently of the main system. Both tanks will be mounted securely to the vehicle chassis and surrounded by a robust, tubular steel protective cage.

B. Power.

Motive Power will be supplied by internal combustion engine, capable of 195 peak horsepower. Approximately 44 gallons (total) of automotive gasoline will be carried in two, explosion proof, racing type fuel cells with rollover valves to prevent leakage while upside down. A fuel shutoff will stop fuel flow in the event of a hard E-stop, rollover, or severe impact.

Electrical power consumption is estimated at 2500-3000 watts continuous, with peak power consumption estimated as high as 4500 watts, not including engine starter usage if required.

C. Processing.

The main vehicle processor is a dual Xeon server with multi threading capability. Redundant hard drives provide storage for data. The server handles most of the processing for the entire vehicle including terrain sensing and image processing. The Inertial sensing unit is based around a Motorola MCS6800 series MCU. The ISU collects inertial guidance data, carries out control orders from The AI/ NAV, and also collects and relays location and vehicle state information for use by the AI/ NAV. The data logging processor (Pentium 4) records data for optimization and improvement of the system after the race.

Sensor data is written onto to a 2D array, or local map, which is oriented and localized using odometry, compass heading, and GPS information as well as 3 axis pitch, roll, yaw, and acceleration data from the ISU. Individual reporting from imaging, laser scanning, map data, and close range (<12m) ultrasonic sensors is weighted and translated to an orthogonal representation of the scanned terrain along with course boundary information, and is written as terrain passability. By interpreting the intended path of travel against the aggregate data of the local map, a path is constructed. This path is expressed via “control points”. A control point defines any location where control inputs are required. These control points are then sent to the ISU as action commands, along with all the specific parameters required to execute the maneuver.

The system classifies objects as either passable or non-passable on the basis of color, visual texture, height, discontinuity with the surrounding environment, or general inconsistency with respect to its goals. A non-passable object or area does not look like either the road or benevolent terrain and therefore is avoided. Non-passable objects would include natural obstacles as well as vehicles or humans. The system updates between 8 and 16 times per second, this should be fast enough to detect moving objects.

D. Internal Databases.

Stored Internal data will include the following:

1. Stored Map Data

The source of our map data will be 2.4-meter resolution commercially available multi-spectral satellite imagery, combined with USGS DEM and DOOQ data sets. This data will be combined to create a simplified 2D map showing road data, and areas with significant elevation change or other relevant features. Stored map data will be retrieved as necessary by the AI/NAV computer and written onto the local map for consideration along with course boundaries and sensor data.

2. RDDF and course segment data

RDDF information will be uploaded and stored for use during the race.

3. Color and Texture reference Data

Terrain reference data will be stored in the form of a pre-loaded terrain reference matrix, which maps color and texture histogram data to terrain passability.

E. Environment Sensing. (See attachment)

Environment sensing will be achieved using a combination of systems. Image processing, laser scanning and close range ultrasonic systems will be used. Color and texture processing data will be used for terrain classification.

Color processing will compare pixel data in the raw image capture against reference samples stored in memory. The texture processing will compare frequency components against reference samples stored in memory. Terrain classification will use both color and texture of known terrain types, stored in a reference matrix, to produce a terrain passability value.

Two cameras will be used. For color analysis a Fire wire digital camera with 1280 x 980 resolution will be used. For texture analysis a monochrome camera, sensitive to near IR will be used. Field of view for both cameras will be approximately 90 degrees horizontally and approx. 70 degrees vertically. Cameras will be mounted approximately 5 feet high with the image center angled downward, corresponding to a point approximately 150 feet from the front of the vehicle. The cameras will cover 180-degree horizontal field of view by rotating with the steering movements of the front wheels. At least one camera will have the ability to swivel and face in a rearward direction.

Two Sick LMS211 LIDAR units will scan a 100-degree field of view in front of the vehicle providing terrain contour data. The units will be mounted along the longitudinal centerline of the vehicle in front and rear. The front unit will be mounted at a height of 3.5 feet. This unit scans at a steeper angle downwards to detect negative terrain features and close range obstacles. The rear unit will be mounted at a height of approx 7 feet and aimed at a point approximately 150 feet in front of the vehicle. The rear sensor will also have the ability to flip and face rearward to enable reverse operation of the vehicle. The flip motion is accomplished by pneumatic operation. Data from these devices will be written to the local map. The primary task of this system is to compliment camera systems and identify hazardous terrain features and discontinuities, such as drop-offs, steep faces or vehicles. Close range ultrasonic sensors will be mounted around the perimeter of the vehicle, at wheel level, to provide 360-degree hazard detection at crawl speeds when other sensors are inoperative or unable to see. Sensor weighting will be configurable accommodate variable conditions.

F. State Sensing.

The vehicle uses 3 axis rate gyros and 3 axis accelerometers to determine attitude and speed changes. Other sensors monitor engine RPM, intake manifold pressure, brake settings, brake hydraulic pressure, fuel level, water temperature, individual wheel speed, transmission gear position, throttle position, and steering angle This information is collected by the ISU and made available to the AI at 8 to 16 HZ. In addition "go-no-go" monitoring exists to detect a failure in critical systems and generate an E-stop.

The AI uses the data to verify maneuver commands have been carried out, predict vehicle position and check for nominal systems operation at any given moment. Accelerometer data is used to slow the vehicle when the road is bumpy, verify stopping and throttle response, and confirm turn data. Odometry and wheel speed are used to determine speed and position. Manifold pressure (vacuum) is used to detect engine braking and assist in gear changes. Other monitors are used to tune and troubleshoot the vehicle systems and software.

G. Localization.

The odometry system uses odometry, inertial, GPS, and digital compass data to determine its location. The DGPS receiver is a Trimble AGPS 114. The unit is available to receive either the USCG beacon or private subscription service. In light of increased positional accuracy requirements, we would like to request the option to use Omnistar satellite DGPS subscription service as the USCG signal may not be reliable in the area. This is a commercially available correction service. Omnistar lists accuracy as " 2-sigma (95%) of significantly less than 1 meter horizontal position error and the 3-sigma (99%) horizontal error will be close to 1 meter". Odometry wheel click resolution is less than 1 foot. When the vehicle is moving GPS will periodically maintain the heading gyro. Compass accuracy is +/- .5 degree but will only be used as a contingency in the event GPS heading information is not available for periodic update of the heading gyro. During normal operation the GPS unit reports it's positional accuracy to the AI/NAV. During GPS outage estimated positional accuracy is calculated as follows:

Accuracy = Last GPS accuracy +[(Odometry system error per unit distance) X (Dist. traveled since last update)]

The value "Odometry system error per unit distance" is continuously updated by averaging the observed error in the odometry system compared to GPS data when available. When GPS data is unavailable the last known value is used.

The current estimated positional accuracy is taken into consideration and compared the lateral course boundary. If the estimated positional accuracy becomes equal to the lateral course boundary, the vehicle will stop and attempt to use GPS signal averaging to improve its position accuracy. When successful the vehicle uses the more accurate position to update the odometry, and resumes movement. If a more accurate position cannot be determined, the vehicle will remain stopped. During normal operation the system navigates using odometry and inertial information. Odometry and inertial information are sent from the ISU to the AI at 8-16 Hz.

These systems are automatically updated once per second by GPS. When the vehicle is stationary, an electronic compass keeps the heading gyro on track. During intermittent GPS outage the system keeps functioning normally, although GPS updating is suspended. During extended GPS outage, the vehicle will operate on odometry and compass information until the accumulated error exceeds the lateral course boundary or GPS is restored.

Terrain outside of Challenge route boundaries is written to the local map as completely impassable. The AI will not consider traversing these areas under any circumstances

H. Communications

No information will be broadcast from the vehicle, and the vehicle will not receive any wireless signals other than GPS signals for positional update.

I. Autonomous Servicing

The vehicle will not refuel during the race. There will be no servicing of the challenge vehicle during the race.

J. Non-autonomous control.

The vehicle is equipped with manual controls located on a stowable pendant to allow moving and positioning the vehicle. The vehicle will not be equipped with radio control or any other remote control capabilities during the Competition or QID.

2. System Performance
   A. Completed tests. –
      1) GPS and some component level tests have been conducted thus far, providing confirmation of design information only. Results of GPS testing indicated normal GPS was only accurate to +/- 3 meters and use of DGPS would be necessary to comply with positional accuracy requirements.
      2) Braking distance tests in a stock jeep Cherokee (3200 lbs, non-anti lock brakes) on loose dirt and gravel were conducted. Stops were severe, causing sliding and loss of heading control. This was meant to find the absolute minimum distance required to stop in an emergency. Braking distance (not including reaction time) was measured from wheel "lock up" to vehicle stop:
         35 mph- 50 ft average (min 48 ft, max 52 ft, 2 stops total)
         45 mph- 75 ft average (min 72 ft, max 79 ft, 4 stops total)

      3) Component level testing and verification. -Carried out on a standard 4 wheel-drive vehicle chassis before assembly and integration on race vehicle. Systems included:
         All individual systems and monitoring devices.
         DGPS reception and accuracy
         LIDAR data analysis
         Image data analysis
      4) Manually controlled test and tune. –Operation of vehicle using a human driver under various conditions and scenarios. Preliminary testing and tuning of the race vehicle platform and following
         a. Proper function of controls
         b. Function of safety features

c. Control reaction time and slew rates
d. Stopping distances
e. Turning capability
f. Rough terrain/ obstacle capability
g. Vehicle state monitoring
h. Chassis tuning
i. Engine tuning
j. Engine cooling system
k. Safety procedures
l. Recovery procedures

Current testing

5) Vehicle GPS/Waypoint navigation test and tune- Operation of vehicle in a GPS/waypoint only navigation capacity without sensing in an obstacle-free environment. Testing and tuning of the following:
    a. Initialization/shutdown procedures
    b. E-stop function
    c. Vehicle positional accuracy and repeatability
    d. Odometry and inertial accuracy and update procedures
    e. RDDF read in and parsing
    f. Stop at specified waypoint
    g. Turn at specified waypoint
    h. Speed control
    i. Course boundary adherence
    j. Closed course accuracy and repeatability
    k. Safety procedures

4) Vehicle integrated system test and tune-Test and tuning of systems and entire platform. Test and tuning of AI and path planning algorithms.
    a. Obstacle detection and reaction
    b. Road following ability
    c. Speed control
    d. Control oscillation
    e. Shutdown and re-acquisition of data
    f. Maneuvering and capability
    g. Optimization of settings
    h. Terrain and navigation problem solving
    h. Multi vehicle scenarios

3. Safety and Environmental Impact

A. The Maximum speed of the vehicle will be limited by to 45 miles per hour. This speed will only be allowed under optimum terrain and course boundary conditions and only with complete sensor agreement. Speed setting algorithms will take into consideration the following and reduce speed appropriately:

Sensed Obstacles
Sensor obstruction

Sensor disagreement
Data discontinuities or gaps.
Length and width of a clear path.
Vehicle roll or pitch angle
Turn radius
Proximity to course boundaries
Proximity to areas identified as impassable on the map database
Wheel slippage
Component failure
Segment speed limit
Smoothness of driven surface (Accelerometer based)
Smoothness of intended path of travel (visual texture based)
GPS Outage
Sudden swerves or heading changes

If less than optimum conditions exist speed will be significantly reduced. At no time will the vehicle attempt to overrun it's sensing capabilities. Maximum obstacle sensing is approximately 250 feet for the vision systems, and 200 feet for the laser scanner.

Estimated Stopping distance

The system updates every 125 ms. At most the maximum time from detection to response would be slightly less than 2 system updates, approx. 250ms. The Pneumatic braking system offers very fast actuation time (<50ms). The maximum reaction time from sensing an obstacle to initiating braking is less than 300 ms (<2 system updates plus brake actuation time), which corresponds to 20 feet at 45 miles per hour (66 ft/sec). Adding the 75-foot measured stopping distance of our test jeep (at 45 MPH) gives a total stopping distance of 95 feet. Because the weight of our race vehicle is 60% of the test vehicle, and has over 30% more tire contact area we expect stopping distances to be reduced at least 10-20%. This should put the stopping distance within the range of the laser system and well within the sensing range of vision. We will verify these figures during testing.

B. Vehicle max range is 400 miles
C. Safety equipment
   2 bladder-style racing fuel cells, equipped with roll-over valves will hold 44 gallons of fuel. A safety shutoff valve will automatically stop all fuel flow to the engine compartment when a hard E-stop, tip over, or ignition shutdown takes place. Fire equipment includes a automatically activated 10 lb Halon 1211 fire suppression bottle, as well as a manually operated fire extinguisher, stored on the vehicle, available for use by safety crews.
   An SAE class 1 rotating amber beacon will be installed providing 360-degree visibility; in addition an intermittent audio warning device will be positioned on the vehicle in accordance with challenge rules.

D. E-Stops.

The vehicle executes e-stops in the following manner:

E-stop “Disable”: signal from the E-stop device goes directly to a dedicated pneumatic braking actuator supplied by the emergency air tank. This system is designed specifically to allow for stopping of the vehicle under hard E-stop conditions as well as in the event of a total loss of pneumatic pressure in the normal braking system. This actuator is designed to stop the vehicle in a minimum amount of distance. In addition the hard E-stop signal turns off the vehicle ignition, and fuel supply.

E-stop” Pause”- Signal from E-stop device triggers messaging from the ISU To the AI/ Nav processor, overriding normal command sequencing. Throttle is immediately cut and brakes applied while the vehicle continues to steer normally. After stopping transmission shifts into neutral while brakes remain on. The vehicle enters “stand by mode” where it continues to process information and detect obstacles, but remains in a parked condition. When the e-stop signal terminates the AI/Nav issues an order to shift into gear, releasing the brake and resuming vehicle motion. Any new obstacles that may have appeared in the intended path of travel would be taken into consideration by local map update, and a new avoidance path would be chosen.

The Manual E-stop buttons initiate a response similar to the E-stop Disable. The emergency braking actuator is energized, and ignition, and fuel are shut down immediately.

External safety equipment

1) The vehicle has 6, mushroom-style manual e-stop switches (push to stop).
2) The vehicle has an external parking brake to prevent inadvertent rolling.
3) The vehicle has a manual gearshift lever allowing manual shifting into neutral gear
4) A line pressure release allows venting residual pneumatic pressure (thereby releasing brake pressure) after a Hard E-stop
5) The vehicle cannot be started unless the manual gearshift and line pressure release are returned to their normal positions.

Manual controls and their locations:

2 Manual e-stop switches will be mounted on upper surface of both right and left side panels (4 switches). In addition, there will be 1 switch centered at the front and rear panels of the vehicle (2 switches)
All other manual controls will be on the rear panel of the vehicle and clearly marked.

Procedure for moving the vehicle:

1. Apply parking brake.
2. Using manual shift lever shift select “N” (Neutral)
3. Release pneumatic line pressure
4. Release parking brake allowing the vehicle to roll.
5. Re-apply parking brake to secure the vehicle

Lifting and towing eyes will be provided and clearly marked for towing and recovery operations.

E. Radiators.

The vehicle presents a minimum of electromagnetic radiators. The laser scanner is a Sick LMS220. This is rated as an OSHA class 1 laser, presenting no hazard to vision. The ultrasonic devices operate at 33khz with an output of 88db.

1) No devices on the vehicle represent an eye or ear hazard.

F. Environmental Impact.

1) The vehicle represents no additional hazard to the environment or roadway surfaces.
2) Maximum physical dimensions of the vehicle:

   Length: 135 Inches
   Width: 72 inches
   Height: 84 inches
   Weight: 2000 lbs

3) The vehicle footprint is approx. 60 square feet. Total tire contact area is approximately 3.5 square feet. Maximum ground pressure is approx 4 Psi.